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Description and Evaluation of a Four-Channel, Coherent 100-kHz Sidescan Sonar

Mark V. Trevorrow
Vincent Myers

Defence R&D Canada – Atlantic

Technical Memorandum
DRDC Atlantic TM 2004-204
December 2004

Canada

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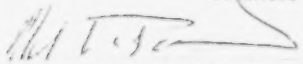

Mark V. Trevorrow

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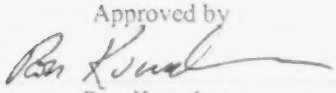

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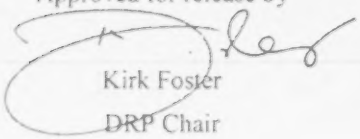

Kirk Foster

DRP Chair

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Abstract

This report documents the design and features of a new, four-channel, coherent 100-kHz sidescan sonar system developed in a collaboration between Defence R&D Canada – Atlantic the Institute of Ocean Sciences (Fisheries & Ocean Canada). This system supports four separate 100-kHz sidescan transducers, with coherent in-phase and quadrature sampling of each channel at 20,000 samples per second. The system has the capability to transmit uncoded, phase-modulated Barker-coded, and swept-FM (chirp) pulse types, with user selectable pulse-lengths up to 10 ms. As part of the acceptance tests, several sidescan sonar applications were demonstrated, including conventional and multi-aspect-angle sidescan, seabed bathymetry through interferometric processing, and the use of chirp pulses. The primary tests were conducted from a small boat in the vicinity of Esquimalt, B.C. in April, 2002. The relatively large horizontal beam-width (3°) of the transducers was found to provide insufficient along-track resolution for reliable seabed mine detection, particularly when compared to very-high-frequency imaging sonars such as the Klein 5500. However, the sonar demonstrated a much greater operational range, in excess of 200 m per side. The use of port and starboard interferometric dipoles was able to map the across-track seabed slope at ranges up to 200 m in roughly 20 m water depth. Measured backscatter frequency spectra were found to have nearly identical frequency content to reference chirp-pulse spectra.

Résumé

Ce rapport documente la conception et les caractéristiques d'un nouveau système sonar 100 kHz à balayage latéral cohérent à quatre canaux, développé en collaboration par R & D pour la défense Canada – Atlantique et l'Institut des sciences de la mer (Pêches et Océans Canada). Ce système fait appel à quatre transducteurs à balayage latéral 100 kHz distincts et permet l'échantillonnage cohérent en phase et en quadrature de chaque canal au rythme de 20 000 échantillons par seconde. Le système a la capacité d'émettre des impulsions non codées, modulées en phase avec codage Barker et comprimées (balayage FM), dont la longueur peut être sélectionnée par l'utilisateur dans une gamme allant jusqu'à 10 ms. Dans le cadre des essais d'acceptation, plusieurs applications sonar à balayage latéral ont fait d'objet de démonstrations, y compris le balayage latéral classique et le balayage latéral angulaire multi-aspects, la bathymétrie par traitement interférométrique et l'utilisation d'impulsions comprimées. Les essais principaux ont été effectués à partir d'un petit navire dans les environs d'Esquimalt (C.-B.) en avril 2002. On a constaté que la largeur relativement grande du faisceau horizontal (3°) des transducteurs offrait une résolution longitudinale insuffisante pour la détection fiable de mines au fond de la mer, en particulier par rapport à des sonars imageurs à très haute fréquence tels que le Klein 5500. Toutefois, le sonar présentait une plage de fonctionnement très supérieure, soit plus de 200 m par côté. L'utilisation de doublets interférométriques de bâbord et de tribord a permis de cartographier la pente longitudinale du fond marin dans des plages allant jusqu'à 200 m à des profondeurs d'eau d'environ 20 m. On a constaté que les spectres de fréquences de rétrodiffusion mesurés avaient un contenu fréquentiel presque identique aux spectres d'impulsions comprimées de référence.

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Executive summary

Introduction

A new sidescan sonar system for research purposes was developed in a collaboration between Defence R&D Canada – Atlantic and the Institute of Ocean Sciences (Fisheries & Ocean Canada). This system supports four separate 100-kHz sidescan transducers, with phase-coherent sampling and the capability to transmit a variety of pulse types. The motivation for this work is to explore the use of advanced sonar concepts for such applications as mine-hunting, ship wake studies, and environmental reconnaissance.

Results

The system was delivered to DRDC Atlantic in April 2003 after several rounds of testing, including field trials in conjunction with trials of a remote mine-hunting system near Esquimalt, B.C. in April 2002. As compared to specialized mine-hunting sonars, the relatively large horizontal beam-width (3°) of the transducers was found to provide insufficient along-track resolution for reliable seabed mine detection. However, the system provided greater operational range and was able to map the across-track seabed slope at ranges up to 200 m through the use of an interferometric dipole technique. The implementation of a swept-FM (chirp) pulse capability was investigated.

Significance of the Results

This report documents the design and features of this new high-frequency sonar system. These initial field trial results demonstrate some of the capabilities and limitations of the system for seabed mine-hunting operations.

Future plans

It is recommended that some further testing and improvements be conducted, specifically in verifying the resolution and signal-to-noise improvement in the chirp-pulse mode, performing an acoustic calibration of the system, and development of a post-processing software suite.

Trevorrow, M & Myers, V., 2004. Description and evaluation of a four-channel, coherent 100-kHz sidescan sonar. DRDC Atlantic TM 2004-204.

Sommaire

Introduction

Un nouveau système sonar à balayage latéral a été développé à des fins de recherche en collaboration par R & D pour la défense Canada – Atlantique et l'Institut des sciences de la mer (Pêches et Océans Canada). Ce système fait appel à quatre transducteurs 100 kHz à balayage latéral distincts et permet l'échantillonnage cohérent en phase ainsi que l'émission de divers types d'impulsions. Les présents travaux visent à explorer l'exploitation de concepts sonar de pointe pour des applications telles que la chasse aux mines, l'étude des sillages de navire et la reconnaissance environnementale.

Résultats

Le système a été livré à RDDC Atlantique en avril 2003 après plusieurs séries d'essai, y compris des essais en conditions réelles menés conjointement avec des essais d'un système de chasse aux mines à distance près d'Esquimalt (C.-B.) en avril 2002. On a constaté que la largeur relativement grande du faisceau horizontal (3°) des transducteurs, comparativement aux sonars de chasse aux mines spécialisés, offrait une résolution longitudinale insuffisante pour la détection fiable de mines au fond de la mer. Toutefois, le système offrait une plage de fonctionnement supérieure, et il a permis de cartographier la pente longitudinale du fond marin dans des plages allant jusqu'à 200 m en faisant appel à la technique des doublets interférométriques. La mise en oeuvre d'une capacité d'émission d'impulsions de balayage FM (comprimées) a été étudiée.

Importance des résultats

Le rapport documente la conception et les caractéristiques de ce nouveau système sonar haute fréquence. Ces résultats d'essai initiaux montrent certaines des capacités et des limites du système pour les opérations de chasse aux mines au fond de la mer.

Recherches futures

D'autres essais et améliorations sont recommandés, en particulier la vérification de la résolution et l'amélioration du rapport signal/bruit en mode impulsions comprimées, l'exécution d'un étalonnage acoustique du système et le développement d'une suite logicielle de post-traitement.

Trevorrow, M & Myers, V., 2004. Description and evaluation of a four-channel, coherent 100-kHz sidescan sonar. [Description et évaluation d'un sonar 100 kHz à balayage latéral cohérent à quatre canaux]. RDDC Atlantique TM 2004-204.

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Acknowledgements

The authors are grateful for the dedicated support provided by the Acoustical Oceanography Research Group at the Institute of Ocean Sciences (IOS), Sidney, B.C., namely Dr. Svein Vagle, Ron Teichrob, Nick Hall-Patch, Rob Reed, and Scott Rose. IOS loaned a prototype 4-channel sonar system for evaluation during the April 2002 trials in Esquimalt, and built a the new system under contract for delivery in early 2003. The excellent boat handling of PO Don Reid, then with ADAC(P), and support from the Fleet Diving Unit (P) in Esquimalt for use of the *RV Tayut* was greatly appreciated. During the post-analysis, some Klein 5500 images were provided by Dr. Anna Crawford of DRDC Atlantic.

1. Introduction

Sidescan sonars are an accepted technology for mine-hunting surveys in shallow waters. Towed sidescan sonar data is generally used to create an *image* of the seabed, so that target highlights, shadows, and seabed texture can be inspected visually. This requires only incoherent amplitude detection within the sonar with modest dynamic range (usually 8 bits), but high spatial resolution (of order cm) is required. The presence of shadows behind objects protruding above the seabed has been found particularly useful for detection of seabed mines. In order to provide high spatial resolution with a manageable transducer size, mine-hunting sidescan sonars generally operate at high acoustic frequencies, usually 200 kHz or greater, with some advanced models using near-field beam-forming to create high along-track resolution. An example of this is the Klein 5500 sonar, utilized by DRDC Atlantic and Trinity Route Survey Office (among others), which uses a 1.25-m long, 12-element array per side operating at 455 kHz. The Klein 5500 sonar offers along-track and across-track resolution of 10 cm and 3.3 cm, respectively, at tow speeds up to 10 knots. Unfortunately, due to the relatively high acoustic absorption in seawater at 455 kHz (roughly 0.1 dB per meter), operating slant ranges with the Klein are limited to approximately 100 m per side, with high-resolution imaging limited to 75 m per side.

Recently, DRDC Atlantic has acquired and evaluated the potential applications for a multi-channel, high-dynamic range, coherently-sampled sidescan sonar operating at 100 kHz. This lower operating frequency offers a compromise between angular resolution and horizontal range, with potential for imaging both seabed and water-column targets in excess of 500 m per side. Additionally, this research sonar has the flexibility for mounting the transducers in a variety of geometries, such as interferometric di¡oles or multiple horizontal angles, and to transmit a variety of pulse lengths, phase, and frequency-modulations. These alternate techniques have the potential to increase signal-to-noise properties and provide additional information about the mine targets. This new four-channel, 100-kHz sidescan system was designed and built through a collaboration with the Institute of Ocean Sciences (IOS, part of Fisheries & Oceans Canada) in Sidney, B.C. Design and construction of the new system took place from April to December, 2002, with subsequent debugging and documentation work continuing through April 2003. This new sidescan system was derived from a long history of sonar development at IOS, focused generally on high-frequency near-surface oceanographic and fisheries applications (see references by Trevorrow et al. 1992-2002).

The primary purpose of this report is to document the specifications and capabilities of this new 100-kHz sonar system. Test data was collected with a prototype system borrowed from IOS, operated on April 16 & 17 in the vicinity of Esquimalt, B.C. The sonar was deployed from a small research boat, the *RV Tayut*, operated by ADAC(P) and FDU(P). These April tests were conducted in conjunction with sea trials of the Remote Mine-hunting System (RMS), which is a semi-submersible drone towing the Klein 5500 sidescan. Thus, high-quality Klein 5500 sidescan images are available for comparison. The final version of this 4 x 100-kHz sonar system was delivered to DRDC Atlantic in April 2003, after some acceptance tests at the pier at IOS.

2. Instrument Description

2.1 Overview and Physical Description

The overall system is composed of a data acquisition PC, a transmitter-receiver electronics unit, and the cables and transducers. The system is designed primarily for vessel-mounted or fixed-location deployments, and would have to be repackaged for use as a towed system. The PC is a standard rack-mounted Pentium IV operating at 2 GHz running Windows 2000, with a 15" flat-screen monitor and a 80 Gbyte hard drive. The PC is equipped with a 8-channel, 16-bit analog-to-digital converter board (Measurement Computing model PCI-DAS6034). Real-time data acquisition and are handled through a custom C++ program developed at IOS. A CD-Rom writer is installed to provide data backup. Serial data from external GPS, Gyro, and pitch-roll sensors are acquired through three separate serial ports, logged into separate files in the prototype systems but incorporated directly into the sonar data files in the final version. The transceiver electronics sub-system (described in section 2.2) generates the transmit pulse, provides impedance matching to the transducers, and coherently mixes down the received echo. The four transducers are connected to the transceiver rack through individual, 30-m-long waterproof cables (20-awg twisted-pair foil-shielded w/drain wire, 0.3" diameter, polyurethane jacket). The cables mate with a 50-cm pig-tail from each sidescan transducer through an Impulse IE33F/M connector pair.

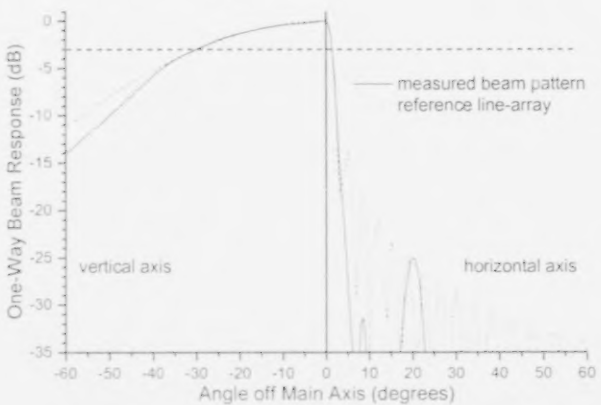


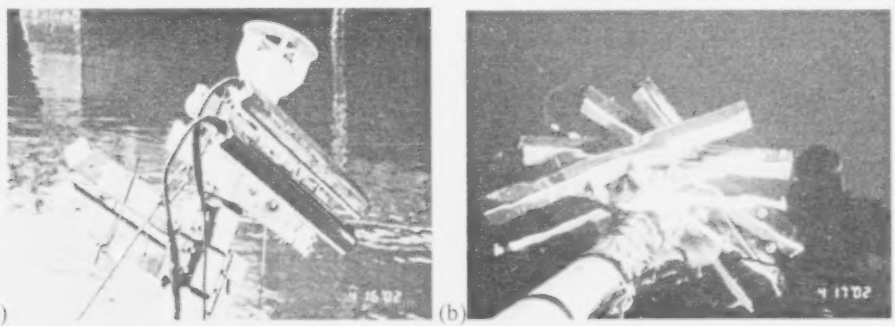
Figure 1: 100kHz EDO Western model 6400 sidescan beam pattern, compared to reference patterns calculated using line-array model with array length chosen to match measurement a -3dB level.

The four sidescan transducers are identical EDO-Western model 6400 sidescans. The transducers are rectangular bars of length 52 cm, width 5.0 cm, and thickness 3.3 cm. These have a fan-beam with –3 dB total angles 3° by 60°. A plot of the beam-pattern adapted from measurements by the manufacturer is shown in Figure 1. The measured beam response is compared to the directivity response $D(\theta)$ for a reference line-array model, i.e.

$$D(\theta) = \frac{\sin(0.5 \cdot k \cdot L \cdot \sin\theta)}{0.5 \cdot k \cdot L \cdot \sin\theta},$$

where k is the acoustic wavenumber (422 m^{-1}) and L is the *effective* array length. This array length parameter was adjusted so that the measured and reference curves agreed at the –3 dB points, hence L = 0.0132 m vertical and 0.253 m horizontal. Overall, the transducer beam pattern has greater directivity than the reference in both axes. In particular, the predicted sidelobes at angles near 5° to 20° in the horizontal pattern are absent, with the first significant sidelobe at –25 dB, 20° off axis. The overall directivity index for these transducers is 22.5 dB. The nominal transmit voltage response and receiver open circuit voltage response are +166 dB re µPa/V at 1 m and –177 dB re V/µPa at 100 kHz, respectively. In the final version the transmitter amplifier drives the transducers with a nominal peak-to-peak voltage of 1300 V, or 460 Vrms, thus generating an on-axis acoustic source level of 219 dB re µPa at 1 m. The nominal transducer impedance magnitude is 300 Ω, thus the equivalent electrical transmit power is roughly 700 Watts rms, with an overall acoustic transduction efficiency of 59%. Transmit power levels were similar for the prototype system used in April 2002.

During the April 2002 trials on board the *RV Tayut* (utility dive tender, approx. 9 m length), the four transducers were mounted onto a 3" diameter pole attached to the starboard side of the boat. With the pole deployed vertically downwards, the transducers were nominally 1 m below the water line. Two configurations were used: (i) in port- and starboard-oriented interferometric dipoles, and (ii) multi-azimuth steering angles. Photographs of the transducer mounting arrangements are shown in Figure 2. In the interferometric dipole geometry, the pairs were oriented athwartships with the wide beam axis vertical, with channels 1&2 to port and channels 3&4 to starboard. In both cases the main transducer axes were oriented downwards approximately 30°. The vertical spacing between the acoustic centres of the transducer pairs was 7.8 cm (port) and 8.2 cm (starboard). In the multi-azimuth mode, the transducers were azimuthally oriented (nominally) -45°, -30°, 0°, and +30° for channels 1-4 respectively, where zero angle is athwartships with positive forward.



(a) (b)

Figure 2: photographs of 4 x 100kHz transducer mounting on *RV Tayut*. (a) interferometric dipoles used on April 16th; photo with pole swung upwards and out of water (b) looking down into the water at multi-azimuth configuration used on April 17th (left is forward).

2.2 Description of Electronics and Pulse Types

The sonar transmit and receive electronics cards and power supplies are contained within a standard 19" rack-mounted unit, 35 cm high. This electronics unit is powered by 110VAC, and has only two connections to the PC: (i) a 44-conductor ribbon cable to the A/D converter and (ii) a bi-directional serial communications line for commands. There are four plug-in connectors on the back for the four transducer cables. Two BNC connectors on the front panel provide an output pulse trigger when operating in an internally triggered mode, or input for an external pulse trigger. Two additional toggle switches on the front panel control AC main power and transmit power on/off.

Overall, the electronic functions are contained within 3 types of custom-designed printed-circuit cards: (i) a single multi-channel controller card, (ii) two x 2-channel transmitter cards, (iii) two x 2-channel receiver cards. The cards are all standard 4.5" x 6" with 44-pin edge-connectors. Block diagrams of the Controller, Transmitter, and Receiver cards are shown in Figures 3, 4, and 5.

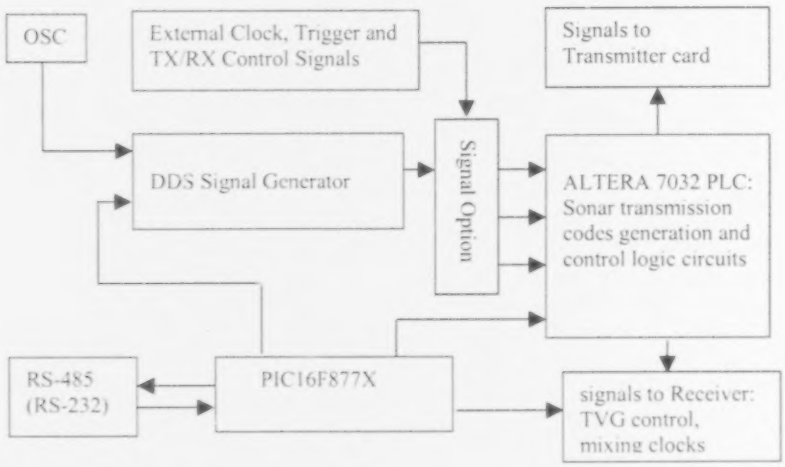

OSC
External Clock, Trigger and TX/RX Control Signals
Signals to Transmitter card
DDS Signal Generator
Signal Option
ALTERA 7032 PLC: Sonar transmission codes generation and control logic circuits
RS-485 (RS-232)
PIC16F877X
signals to Receiver: TVG control, mixing clocks

Figure 3: block diagram of the sonar Controller card.

The Controller card generates the necessary clock signals, transmit waveforms, time-varying and fixed gain control voltages, and triggers. The heart of the Controller is a PIC 16F877 micro-controller chip. The PIC translates serial commands from the PC (RS232 format) and in turn commands a synthesizer (Analog Devices AD9835) and programmable logic chip (PLC, Altera 7032) to generate the transmit and mixing signals. The PIC also controls the overall cycle timing and triggering, and output of the gain control voltage. The time-varying gain (TVG) is controlled through output of 8-bit realizations of a gain curve from a D/A converter, which along with a fixed gain offset is then used to control the gain on a voltage controlled amplifier (Analog Devices AD602). The output gain curve will be described in section 2.3. The carrier and mixer clock signals are derived from an Analog Devices AD9835 synthesizer. It takes an 8 MHz crystal clock signal and divides it down to 400 kHz, creating

both the in-phase and quadrature mixing frequencies. Then the Altera PLC is used to divide the output down to the 100 kHz carrier and mixing frequencies, and to generate the chirp or phase-modulated pulse types.

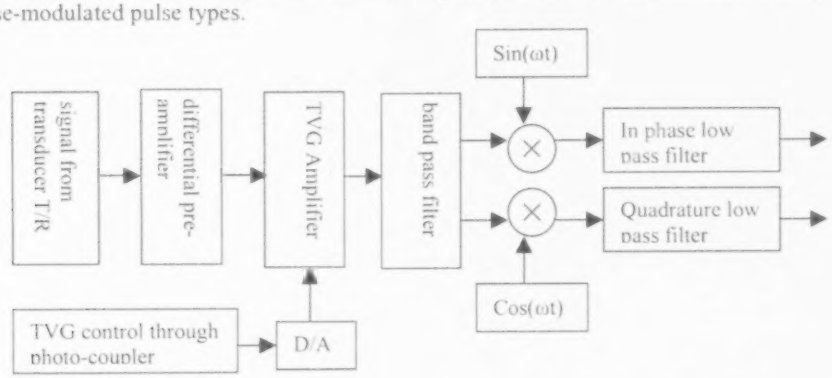


Figure 4: Block diagram for one channel on Receiver card (two channels per board); output to A/D card on data acquisition PC.

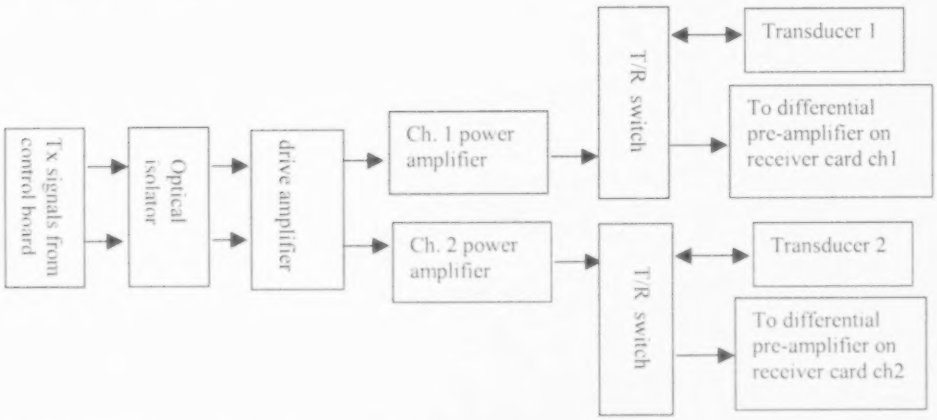


Figure 5: block diagram for two channels on the sonar Transmitter card.

Each Transmitter card takes an input transmit signal (generated by the Controller), amplifies it, and then drives two transducers. To reduce cross-talk of digital signals into the receiver, the input signal from the Controller is buffered using optical isolators. The power amplifiers boost the output voltage to approximately 1300 Vpp, delivering around 700 W electrical to the transducer. An impedance-matching inductor tunes the transmit circuitry to maximize power delivery. A diode-network transmit-receive switch protects the receive pre-amplifier from the transmit voltage. The transmitters are supplied through a 28 V, 5 A linear power supply, buffered by 5 x 0.1 Farad capacitor bank.

Each Receiver card takes the return echo from two transducers through a pre-amplifier and main TVG amplifier before band-pass filtering and mixing. Again, to control digital cross-talk the TVG control voltage is optically isolated. Each channel is band-pass filtered (-3 dB

corners at 90 and 110 kHz), then homodyned by mixing with sine and cosine versions of the 100-kHz mixing signal. The two output signals from the mixer (four signals overall on each card) are DC-coupled and low-pass filtered, then sent over to the A/D converter on the data acquisition PC. A typical frequency response of one receiver channels is shown in Figure 6. The band-pass -3 dB corner frequencies are 95 Hz and 5.4 kHz. An electronic calibration facility is built into the data acquisition program to allow calculation and subtraction of DC offsets in the in-phase and quadrature samples for each channel.

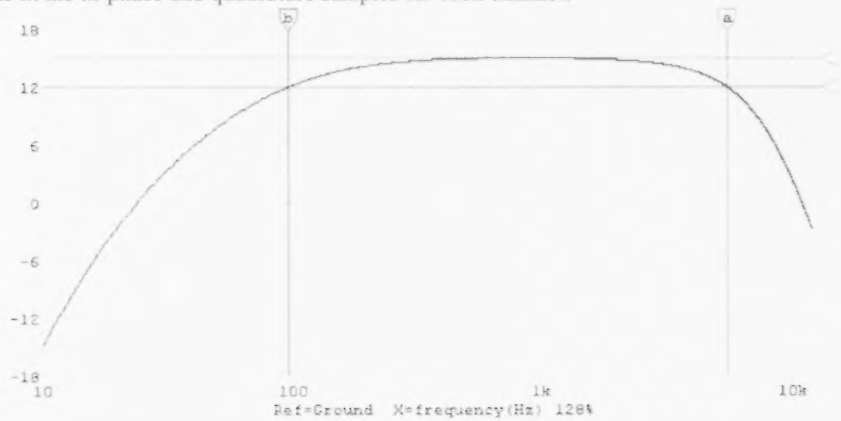


Figure 6: frequency response of typical receiver channel after mix-down and low-pass filtering.

The data acquisition program resident on the PC has facilities for commanding the PIC micro-controller, which in turn controls the pulse generation, ping rate, maximum sampling time, and time-varying gain functions. There are three distinct types of pulses that can be generated: uncoded, phase-encoded, and chirp. These are specified through three parameters: code type, cycles per bit, and code-length in bits. For uncoded pulses, any combination of cycles and bits is allowed, up to 10 ms total length. For phase-encoded pulses (useful for Doppler processing, see Refs. 1,3,4,5) the pulse structure is multiple repetitions of Barker codes, with choices of 4, 5, 7, 11, 13 bits. Owing to bandwidth limitations, it is recommended that the cycles per bit parameter be set for at least 10. Typical settings for this would be 10 cycles per bit, 7-bit code, and 28 bits overall, which creates a 2.8 ms pulse that has 4 repetitions of a 7-bit Barker code. For the chirp pulse, the bit length is fixed to 50 μs. A *code_length* parameter then determines the overall pulse length, e.g. *code_length* of 20 produces a 1 ms pulse. The chirp is generated by discretizing the frequency interval 95 to 105 kHz into *code_length* steps, e.g. in a 1 ms pulse there are 20 x 500 Hz steps. The maximum chirp length is 10 ms. The ping rate parameter can vary from 0.1 to 10.0 Hz in steps of 0.1 Hz, controlled by the PIC, or can be set independently via an external trigger. The maximum sampling time, which determines the number of samples acquired at the 20 kHz sampling rate, is currently limited to 1000 ms (~750 m slant range).

Aside from signal generation limits, the maximum transmit pulse length is limited by the acceptable level of voltage droop created by power drain from the transmit power supply. The energy stored in the 5 x 0.1 Farad capacitors is intended to buffer this effect. Laboratory tests with the 4 transducers active showed the transmit signal dropping from 1320 Vp-p to 1270 Vp-p (i.e. 4%) over a 3.2 ms pulse. Also, over the same pulse length the base transmit

power supply voltage fell from 28 V to 26.9 V. In order to keep transmit voltage droop to less than 10%, pulse lengths should be kept less than 8.2 ms.

For the case of a chirp pulse transmission, the maximum pulse length is limited by hardware to less than 10 ms, or using 200 x 50 μs steps. The limitation stems from a loss of resolution in the frequency division process, which allows for 41984 possible values from 95 to 105 kHz. However, the synthesizer can only accept values that are multiples of 128, so that above 200 steps some ambiguities can occur.

The data acquisition program stores the raw in-phase and quadrature samples, along with headers for ancillary time, position, and attitude data, in a PC binary file. An explanation of the various binary file formats are given in Appendix 1. The fundamental sonar data are composed of 16-bit unsigned integers of in-phase and quadrature samples from the four sonar channels. These unsigned integers have a zero value at 32768 counts and an input range of ±5.0 V. In the prototype system (April 2002) and in the final version the A/D sample rate was set at 20 kHz.

2.3 Time-Varying Gain and Internal Noise Tests

The time-varying gain (TVG) amplifier is used to partially correct for effects of geometric spreading and absorption losses. For any quantitative acoustics applications this curve must be known. Also, the intrinsic noise levels in the receiver electronics, which are amplified by the TVG, impose some limitations on system performance.

The PIC microprocessor generates the TVG control voltage for all four channels by clocking out samples from memory through an 8-bit D/A converter. Three parameters control the TVG time-variation: a delay time, t_0, a rise time, t_1, and fixed gain offset, G_0. After the pulse trigger, the TVG does not start until after a delay period which is the sum of the transmit pulse length and the delay time parameter, t_0. During this delay period the TVG has gain G_0. After this the PIC begins clocking out the time-varying control voltage, which has a form roughly $24*\log_{10}[\text{range}] + 0.066*\text{range} + G_0$ (in deciBels). The TVG continues to rise until it reaches a time-after-trigger which is the sum of the pulse length + $t_0 + t_1$, or it reaches the maximum gain value. After this time the TVG remains constant until reset by the next pulse trigger. The minimum and maximum TVG values are –20 and +60 dB.

The actual TVG curve can be measured by recording echo data with the transmit power disabled, in essence using the intrinsic electronic noise as a constant amplitude source. Figure 7 shows an example taken from acceptance tests at IOS on March 23, 2003. The data intensity (in dB) was computed from the signal amplitude (i.e. square-root of sum of in-phase-squared and quadrature-squared), rms averaged in range to a 10-kHz sampling rate and rms averaged over 100 pings. In this case the electronic noise is dominated by 60 Hz electrical cross-talk (common to interior test tanks), creating the *ripple* effect with a roughly 16 ms (12 m) time scale. The signal level shows only minor variations between the channels, so only a single TVG function will computed. The small variations in overall amplitude between channels can be lumped into individual channel calibration factors (if desired). A non-linear least-squares fit was performed on a sub-set of the intensity vs. range for each channel, with resulting TVG curve (in dB) –23.9 + 24.0*log10[range] + 0.066*range. The TVG offset

value (-23.9 dB) defines the strength of the internal noise source relative to systemic gain factor, and will be different for each installation and location.

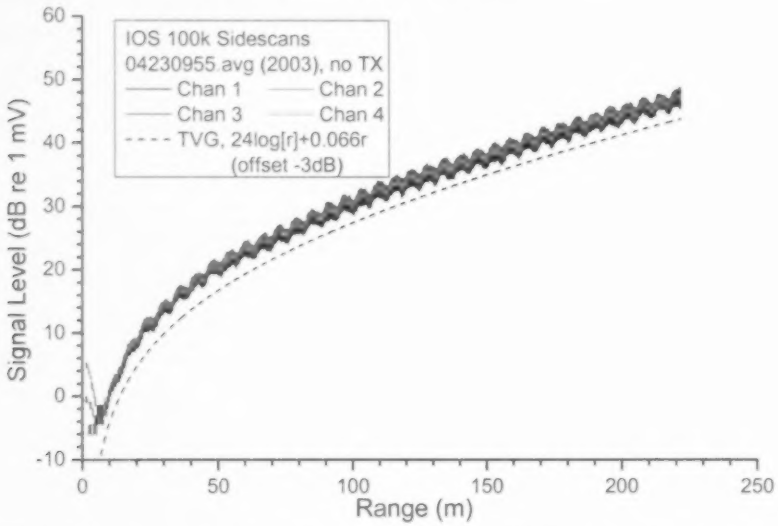


Figure 7 Signal intensity vs. range for TVG test, averaged over 100 pings taken 0955h, Apr. 23, 2003 at IOS. TVG control parameters were t_0 = 2 ms, t_1 = 300 ms, and G_0 = -20 dB, with a 0.4 ms pulse length. Transmit power was disabled. Best-fit TVG curve offset by –3 dB for clarity.

In this example the internal noise level in the electronics and cables is reasonably high, as it was recorded in an enclosed tank room with no effort to optimize the grounding. This worst-case internal noise was dominated by 60 Hz AC line noise. The true noise level appears within the first few milliseconds, before the TVG begins its rapid increase, with a value near -6 dB re mV. In this test the fixed gain was -20 dB, thus the true internal noise level was +14 dB re mV, or 5 mV (rms). Other tests have put this internal noise voltage at less than 1 mV. The maximum rms amplitude before A/D clipping is 7070 mV, or 77 dB, so that in this case there is at least 20 dB signal-to-noise headroom at ranges up to 300 m.

3. Conventional Sidescan

This 4-channel, 100-kHz system can be employed as a traditional sidescan sonar to perform such tasks as object detection and sea bottom mapping. Two days of sea-trials were conducted on April 16th and 17th, 2002 near Victoria, BC to determine this suitability. These trials were conducted in conjunction with towed sidescan (Klein 5500) trials using the remote mine-hunting vehicle *Dorado*. In these trials the 4 x 100-kHz sonar transducers were rigidly mounted on a pole over the side of a small vessel, with no heading or attitude sensors. This was not an ideal mounting arrangement for seabed sidescan operations, for several reasons:

1. vessel motion artefacts were directly coupled into the sidescan data, with no direct measurement of vessel pitch, roll, and heading.
2. for water depths greater than roughly 20 m, the transducer altitude was generally too large, reducing the contrasting shadows often used for seabed object detection.
3. the transducer geometry allowed some contamination from ocean surface scattering and bubbly vessel wakes.

Thus in evaluating comparisons between this system and high-quality towed sidescan data delivered by the Klein-Dorado system, it is important to separate problems due to this non-ideal mounting geometry from those limitations inherent in the sonar system itself. Comparisons will only be attempted in locations that minimized some of the mounting problems (i.e. from calm conditions and water depths near 15 m). In this section, the raw 4-channel sidescan sonar data was converted to the same format (*.SDF) as the Klein 5500 sidescan. This enabled input and processing using the DRDC Atlantic *Sonar Image Processing System* (SIPS), also used to process the Klein sidescan data.

As in all sidescan sonar data, the effects of absorption, attenuation, and transducer beam-pattern were evident in the echo intensity vs. range variations observed with this system. Additionally, in data from April 16th, 2002 where an interferometric dipole geometry was used, a number of transmit interference lobes were observed. For the purposes of generating sidescan sonar imagery, these effects must be compensated for and the data scaled to an appropriate dynamic range. The first step is to normalize the sonar data by dividing the intensity of each pixel at a given slant range by the ping-averaged intensity at that range. Then this normalized intensity is re-scaled into a 0 to 255 dynamic range for imaging purposes. Figure 8 shows a comparison of raw (un-normalized) and normalized 100-kHz sidescan images. The un-normalized image is dominated by the early seabed returns with several interferometric lines near nadir, whereas the normalized version enhances image detail for objects at greater slant range. The normalization process has removed some, but not all, of the near-nadir interference lines. This incomplete beam-pattern compensation results from a broadening of the interference line structure due to ping-averaging in the presence of transducer rolling motions. This could have been at least partially alleviated by using a single transmit transducer per side, rather than an interferometric dipole.

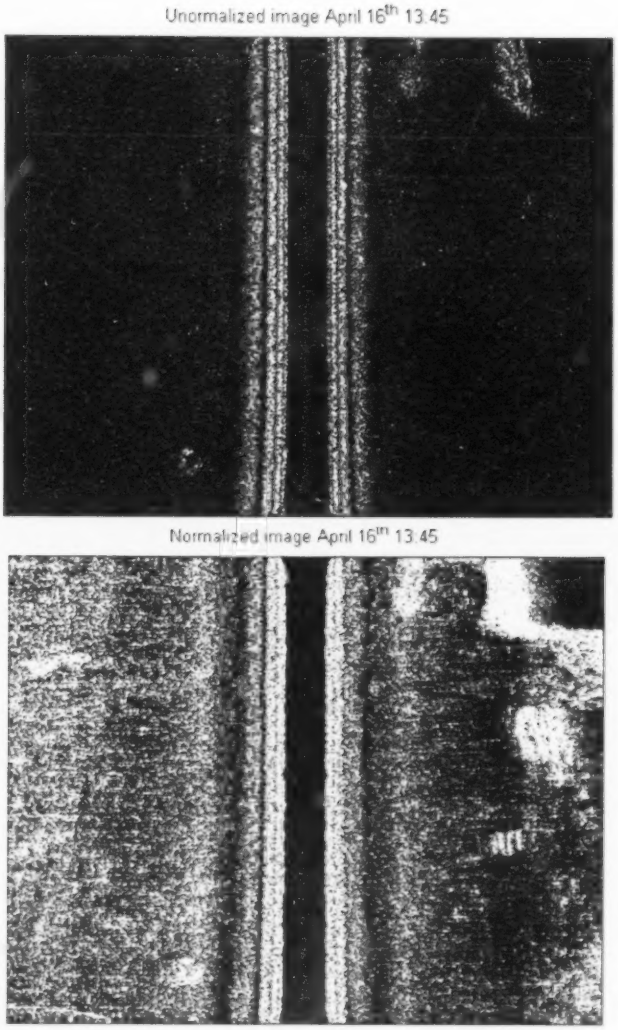


Figure 8: Comparison between the un-normalized and corresponding normalized 100-kHz imagery. Maximum slant range is 185 m.

The next step in sidescan sonar processing is known as geo-coding, where the geographic coordinates (UTM or Latitude, Longitude) of each pixel at each ping is calculated. For this calculation, the instantaneous position (DGPS), sonar altitude, and sonar orientation (pitch, roll, heading) must be known. In this case there was no gyro-compass to give heading information, so heading had to be extracted from the DGPS course made good, averaged over a 10 s running window. Pitch and roll were left unresolved, in essence assuming minimal

vessel motion. This geo-coding is applied to each pixel from each ping in a file, and then *mosaics* of geo-coded data can be pieced together from multiple geo-coded files.

The sonar altitude (essentially water depth) at each ping was calculated from the sidescan sonar data itself. The altitude was calculated as the slant range corresponding to the first strong seabed return, identified by a combination of echo-intensity above a threshold and a maximal first derivative of intensity vs. range. This altitude was conditionally accepted only if it occurred within a narrow window (±0.2 m) around the previous ping altitude, and the resulting altitude vs. time series was also smoothed. This windowing and smoothing of the altitude is done to prevent objects in the water column, or occasional weak bottom returns, from drastically changing the altitude.

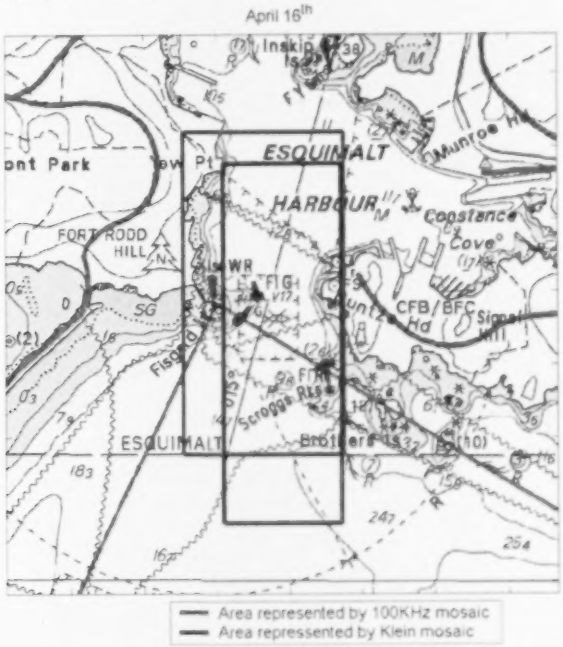


Figure 9: Comparison chart of the bounding boxes covered by the 100-kHz system (red) and Klein 5500 (blue) survey mosaics shown in Figure 10.

Evaluation of the resulting 100-kHz sidescan sonar image quality can be seen from side-by-side comparison of seabed mosaics with the Klein 5500 towed sidescan (Figures 9 - 11) near the entrance to Esquimalt harbour, B.C. In this trial the 4 x 100-kHz sonar used a 0.4 ms pulse transmitted at 2.0 pings per second, with the vessel traveling roughly 4 knots (2 m/s). In general, the 100-kHz system showed a wider swath coverage, up to 185 m per side as opposed to 75 m per side with the Klein. This enabled the 100-kHz system to image the rocks on either side of the harbour entrance (see Figure 10 left). However, the 100-kHz mosaic is heavily contaminated with motion artefacts, particularly the unresolved roll and yaw, and some sea-surface scattering effects. The cross-track striations are due to rolling of the vessel. It is also clear that the normalization process has not completely removed the interferometric lines (the along-path parallel lines near nadir). Use of a single transmit transducer per side

(rather than an interferometric dipole) would have rendered the system much less sensitive to vessel rolling motions. A potential solution would be to make a data-adaptive, beam-pattern correction on a ping-by-ping basis, however the SIPS software is not presently configured to do this. Conversely, the Klein mosaic is largely uncontaminated, except for some tenuous wake artefacts from the escort boat (the most obvious being in the southerly part of the Klein mosaic, Fig. 10 right, just after the turn to the SSE).

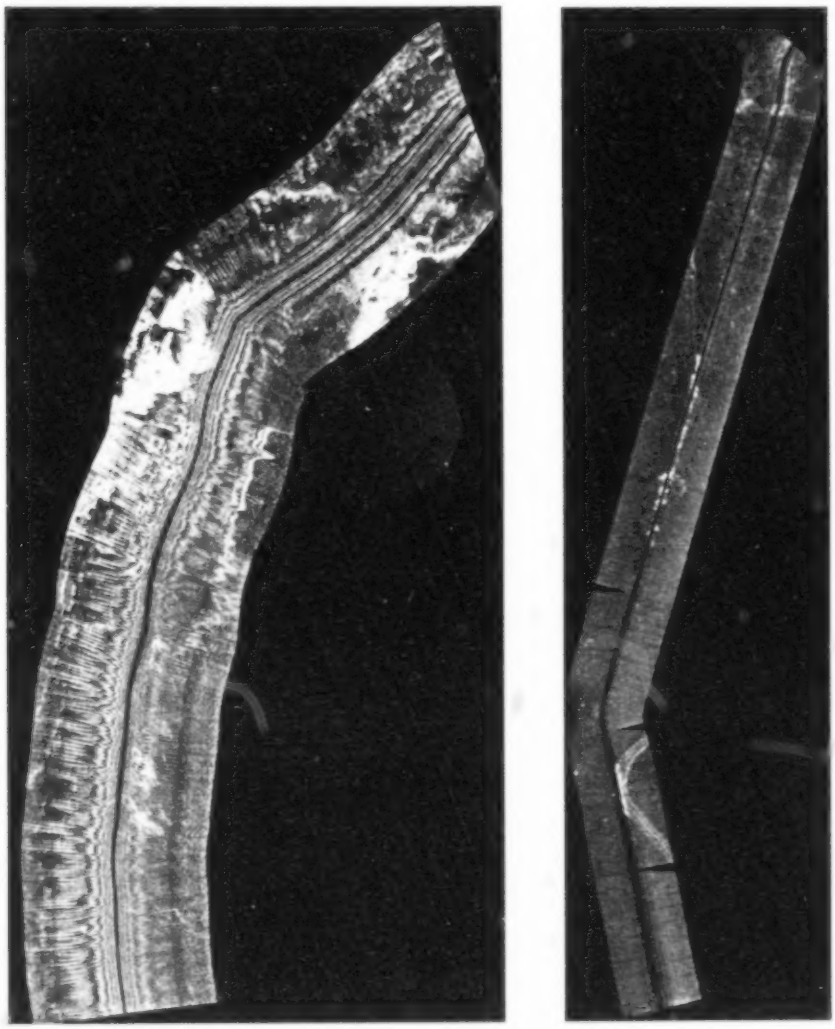


Figure 10: Comparison of sidescan mosaics near the mouth of Esquimalt Harbour using the 100-kHz sonar (left) and Klein 5500 sonar (right). 100-kHz swath width was 185 m per side, while the Klein sidescan swath width was 75 m per side.

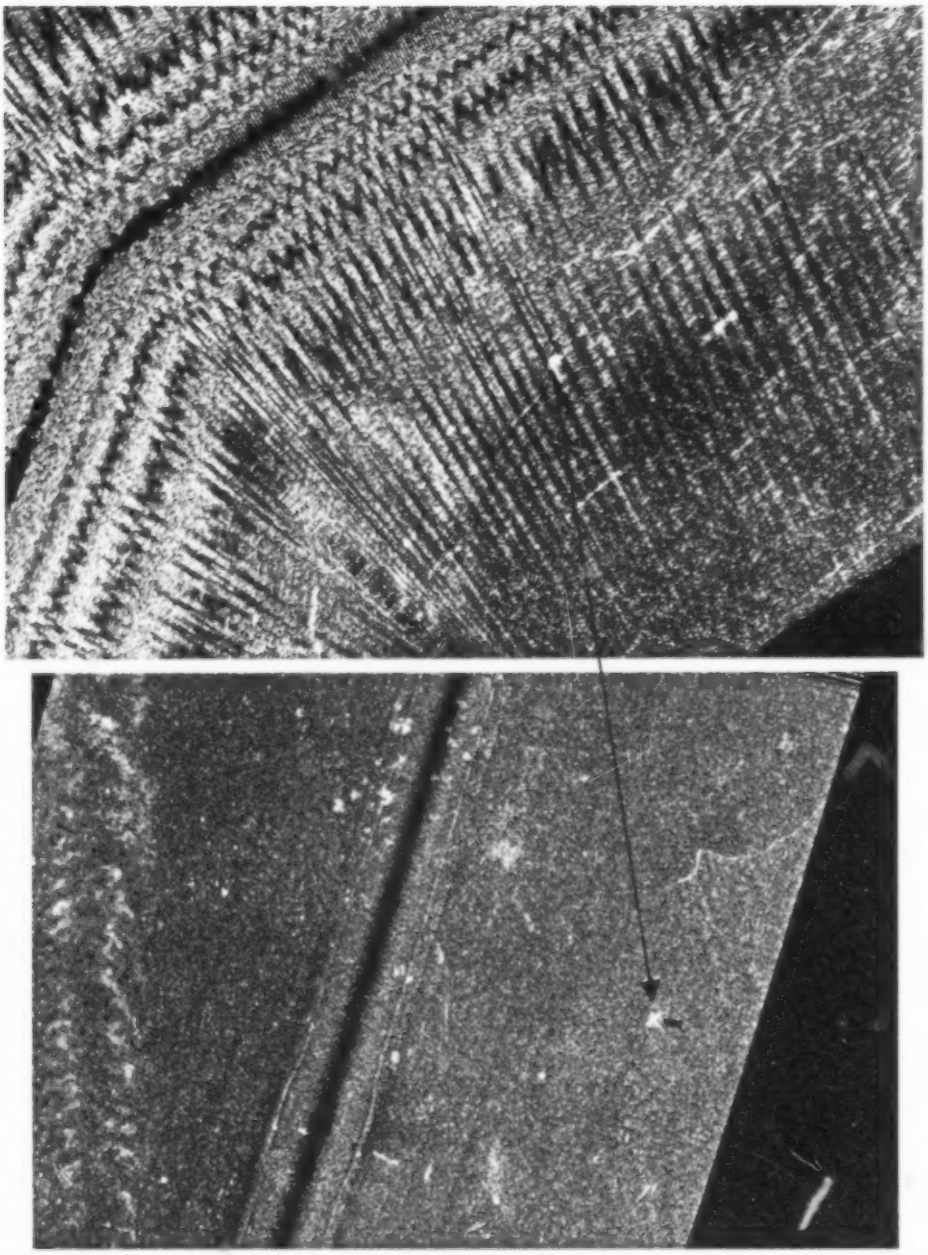


Figure 11: Close-up comparison of seabed object detected with both 100-kHz sonar (upper) and Klein 5500 sidescan (lower) near the mouth of Esquimalt harbour. Mosaics approximately matched in scale.

Figure 11 shows a detailed comparison of a seabed object common to both 100-kHz and Klein 5500 mosaics. In the Klein mosaic, structures within the target echo highlight and shadow zone can be resolved, as well as the shapes and sizes of many nearby objects (such as logs and cables). Since the water depth in this area was approximately 12 m, both the Klein 5500 and 100-kHz sonars were deployed at similar depths (roughly 1.5 m, the Klein towfish was docked), thus both would have insonified this object with similar grazing angles. Ignoring the obvious motion-induced artefacts, the 100-kHz sidescan mosaic shows a lower resolution version of the echo highlight, with little evidence for an acoustic shadow. Another feature common to both mosaics is a seabed cable trending away to the NE, which is clearly visible for more than 150 m in the 100-kHz data. However few of the other seabed targets seen in the Klein mosaic are visible in the 100-kHz. The fundamental difference here is the relatively wide horizontal beam-width (3°) of the 100-kHz transducers. This beam-width implies an along-track resolution that increases with range, such that by 100 m slant range the along-track resolution lies near 5.2 m. Even if the motion artefacts could be removed, this angular resolution is clearly insufficient for resolving the detailed shape of seabed mines with dimension of order 1 m or less. The Klein 5500 sonar has along-track and across-track resolution of 10 cm and 7.5 cm, respectively, approximately independent of range due to its near-field focusing capability. With the 100-kHz sonar operating at a 2 Hz ping rate and the vessel traveling at roughly 2 m/s, even a small, point target would be visible in the beam for at least 5 or 6 pings. This effectively broadens the apparent along-track dimension of a given target. Note that the 100-kHz across-track resolution (near 10 to 30 cm, dependent on pulse length) is comparable to the Klein.

4. Multi-Aspect-Angle Sidescan

By orienting the four 100-kHz sidescan transducers each at different horizontal angles, it has been suggested that multiple *looks* at a given seabed object can be acquired in one pass. When combined, data from these multiple look angles should yield greater information on the target structure. To evaluate this concept, a series of sea-trials were conducted on Apr. 17th, 2002 over a practise mine-field, and a ship-wreck in 65-m water depth. In water depths (i.e. altitudes) greater than 40 to 50 m, the system did not have the necessary angular resolution nor grazing-angle geometry to resolve these small seabed mines. However, reasonable quality images of the ship-wreck were acquired. The four transducers were oriented *approximately* at -45°, -30°, 0°, and +30° with respect to the starboard beam of the vessel (positive forward, angles ±10°), for channels 1 – 4 respectively.

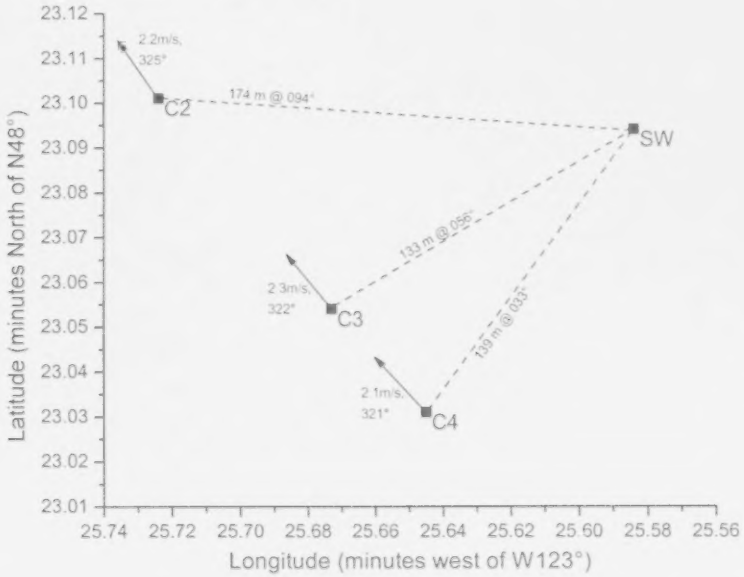


Figure 12 Position plot of ship-wreck (SW) and locations of 100-kHz multi-azimuth images (C2, C3, C4 denote channels) taken 1102h, April 17th, 2002. Labels indicate vessel speed and heading over ground, and horizontal distance and bearing from detection location to shipwreck.

The actual transducer orientation angles can be extracted from the field data through knowledge of the ship track, vessel heading, and object location. In the case of this particular ship-wreck, the position was well-known from repeated surveys with the Klein 5500 sidescan on the Dorado vehicle. Figure 12 shows a position plot of the ship-wreck and 100-kHz sidescan detections in Chans. 2, 3, and 4 as the survey vessel passed to the south-west heading approximately 322°. The ship-wreck was not imaged in Chan. 1 as the boat turned to starboard shortly after position C2. The vessel speed and heading over ground were calculated from the DGPS positions (1 fix per second), and this heading was assumed to be

identical to the vessel heading (i.e. assuming no transverse velocity component due to tide or wind). The closest-approach distance (near Chan 3 detection) was approximately 132 m horizontal, or 147 m slant range in this 65-m water depth. The calculated horizontal distances were in reasonable agreement (< ±5 m) with the observed slant ranges (between 145 and 190 m) for each channel. The particular horizontal offset angle for each transducer was then calculated as the angular difference between the vessel heading and bearing to the ship-wreck at the point of detection, hence -39°, -4°, and +18° for Chans. 2 - 4 respectively. With these offset angles, geo-coding of the sidescan data from each channel was performed using standard methods as outlined in Section 3.

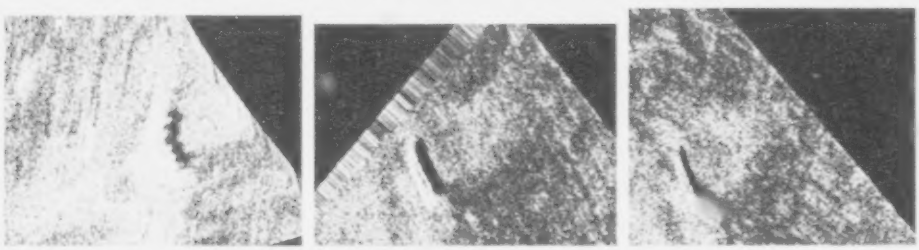


Figure 13 Multiple 100-kHz sidescan geo-coded views of 65-m deep ship-wreck SSE of Esquimalt, B.C. taken at 1102h, April 17th, 2002: (left) Chan. 2 oriented 39° aft of beam, (middle) Chan. 3 oriented 4° aft of beam, and (right) Chan. 4 oriented 18° forward of beam.

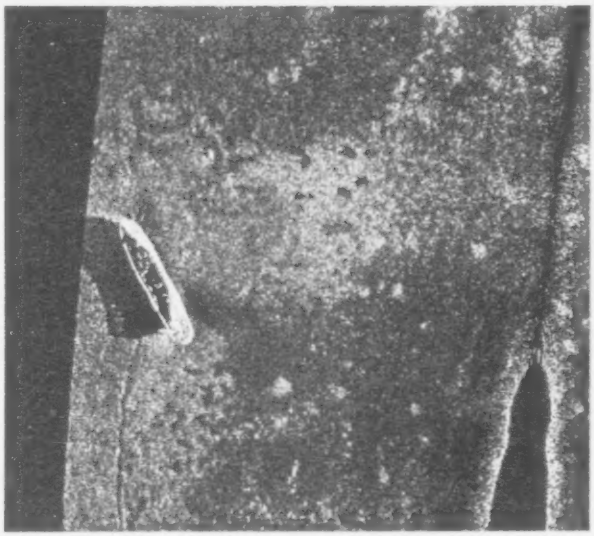


Figure 14 Klein 5500 sidescan geo-coded image of the 65-m deep ship-wreck SSE of Esquimalt, B.C., from April 2002 surveys. Wreck located at N48° 23.094', W123° 25.584', and is 30 m long by 5.5 m wide. This is the same ship-wreck as in Fig. 13.

Figure 13 shows the resulting geo-coded images of the ship-wreck taken with the three different 100-kHz sidescan orientation angles, and can be compared with the Klein 5500

sidescan image in figure 14. Once again the high-resolution Klein 5500 image is clearly superior, although it should be remembered that the Klein 5500 image was acquired from a slant-range of roughly 65 m, about one-half to one-third the slant range used for the 100-kHz. Furthermore the Klein was towed at a near-optimal altitude of approximately 10 m above the seabed, whereas the 100-kHz system was at an altitude of 65 m. Although the ship-wreck is clearly recognizable, the three 100-kHz images suffer from the combination of motion-induced artefacts (particularly Chan. 2, Fig. 13 left) and the reduced angular resolution of the transducers. As compared to the Klein sonar image, none of the details of ship-wreck shape nor any of the deck features (the ship-wreck is upright) were resolved by the 100-kHz system. Also, the anchor drag feature to the south of the ship-wreck in the Klein image was only faintly resolved in the 100-kHz Chan. 2, and not in the others. However, all three 100-kHz images show a shadow, thus allowing at least a rough calculation of the ship-wreck height above seabed. The image from 100-kHz Chan 3, oriented roughly athwartships and thus the most similar in geometry to the Klein image, shows the shipwreck to have a similar orientation and a fairly uniform shadow.

The three different looks from the 100-kHz system, although close, do not exactly overlay each other when geo-coded. This is a result of insufficient transducer orientation information, specifically the lack of a gyro-compass measurement at each sonar ping. Clearly, the assumption that vessel heading is the same as the DGPS heading-over-ground is insufficient for this purpose, particularly in a relatively small vessel perturbed by wind, waves, and tide. To obtain positional alignment to better than 1 m at a slant range of 150 m would require a transducer heading accuracy better than 0.4°. A heading accuracy of ±0.1° is achievable with modern gyro-compasses, and later versions of the 4 x 100-kHz system software were modified to record standard gyro-compass input.

5. Interferometric Sidescan

The coherent in-phase and quadrature sampling scheme of this 4 x 100-kHz sidescan allows multi-element beam-forming concepts to be used. This could allow, for example, the mapping of seabed elevation in addition to simple backscatter intensity. Also, the vertical angle to objects in the water column could be extracted. Data to evaluate these concepts was collected with the sidescan transducers configured in port and starboard interferometric dipoles were conducted on April 16th, 2002 near Esquimalt harbour, B.C.

The first interesting feature of the interferometric dipole mounting schemes was the generation of interference lobes in the transmit beam-pattern (both transducers of each dipole pair were used as transmitters). In this case the transmit pattern was a coherent superposition of the pulses from the two transducers. For the case of a two-element array with vertical spacing s, the response at angle θ (relative to horizontal) is

$$B(\theta) = \frac{\sin\left(\frac{1}{2}kL\sin(\theta-\theta_0)\right)}{\frac{1}{2}kL\sin(\theta-\theta_0)}\left[F\left(t-\frac{2s}{c}\sin\theta\right)+F\left(t+\frac{2s}{c}\sin\theta\right)\right]$$

where the first term is the standard line-array beam pattern response (i.e. as in Fig. 1) with k = acoustic wave-number, L = array length (0.0132 m), and θ_0 is the transducer vertical steering angle (typically 30°). The function $F(t)$ is the transmitted pulse, assumed to be identical for each transducer element. As the typical transducer separation is larger than the acoustic wavelength, the transmit beam response will have a complicated interference structure. Using a typical transducer separation of 80 mm, the resultant transmit beam pattern will be as shown in Figure 15.

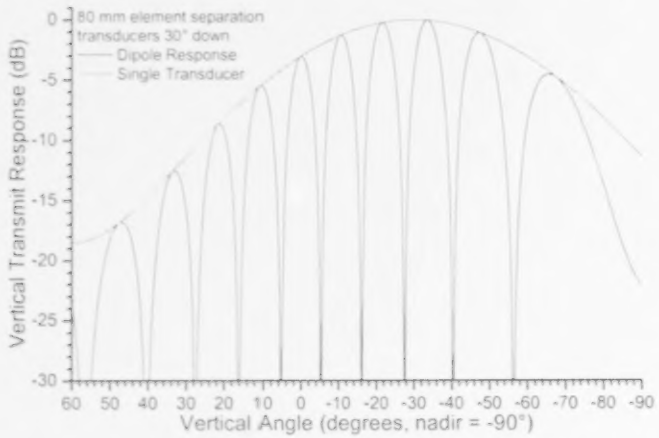


Figure 15: Comparison of single and dipole vertical transmit response. Assumes transducer vertical separation of 80 mm and 30° depression angle.

This complicated transmit beam response creates a non-uniform seabed insonification, giving rise to a series of peaks and valleys in the seabed echo, as shown in Figure 16. In particular, note that there are five distinct peaks in the interferometric intensity vs. range curve, with a

corresponding number of peaks between nadir and horizontal in the vertical beam-pattern (Fig. 15). In the field data, ping-averaging in the presence of vessel rolling motions fills-in the beam-pattern nulls, such that the typical peak to null intensity ratio is roughly 5 dB (not 30 dB as predicted in Fig. 15). This ping-averaging in the presence of roll creates a problem when attempting to normalize the sidescan intensity, as mentioned in Section 3. In principle, this interferometric beam-pattern could be fit to the intensity vs. range curve at each ping, extracting an instantaneous measure of the sidescan depression angle and allowing a more complete removal of the beam-pattern intensity variations. The normal, single-transducer beam-pattern is largely featureless and therefore much less sensitive to vessel roll motions.

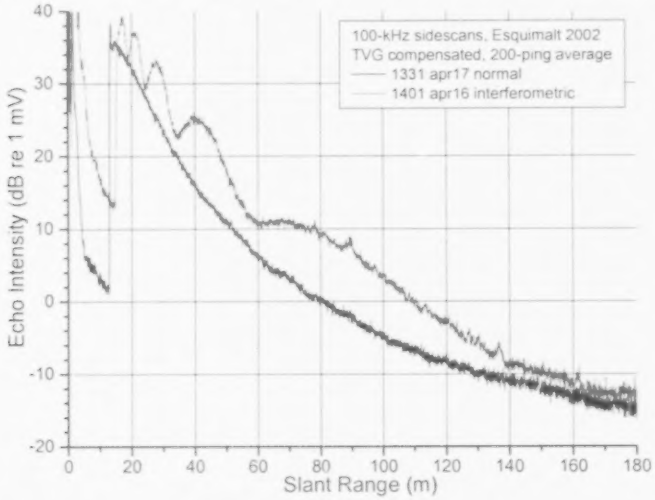


Figure 16 Comparison of normal (single-channel) and interferometric sidescan intensity vs. range curves, taken in April 2002 surveys near the entrance of Esquimalt harbour.

On reception, the phase lag between the two transducers can be used to estimate the arrival angle. For a vertically-oriented dipole, echoes arriving with at grazing angle θ (with respect to horizontal) will induce a phase lag ϕ given by

$$\phi = k \cdot s \cdot \sin\theta - 2\pi \cdot n ,$$

where n is an integer ≥ 0, k is the acoustic wavenumber (425 m^{-1} at 100 kHz) and s is the transducer vertical spacing (nominally 7.8 cm). The phase lag can be estimated from the covariance function, $C(t)$, between the two complex echo time-series, denoted $A(t)$ and $B(t)$ (remember that each of the complex echo time-series has a *real in-phase* component and an *imaginary quadrature* component). This calculation is similar to that performed for Doppler velocity estimation. The covariance function is then computed from the complex product of A and B, averaged over a pulse length, i.e.

$$C(t_j) = \sum_{m=1}^{M} A^*(t_{j+m}) \cdot B(t_{j+m}) .$$

The covariance averaging is necessary to reduce the phase variance. For example with a 0.4 ms pulse, $M = 8$ samples at the 20 kHz data sample rate, corresponding to a 30 cm range bin. Finally, the phase lag is the simply the phase-angle of this complex product, i.e.

$$\phi = \arctan\left[\frac{\mathrm{Im}[C(t)]}{\mathrm{Re}[C(t)]}\right].$$

Then for the case of seabed back-scatter to a transducer located near the sea-surface, assuming no acoustic refraction effects, the grazing angle as a function of slant range, r, can be calculated using simple geometry, i.e.

$$\theta = \arctan\left[d(x)/r\right],$$

where $d(x)$ is the seabed depth (below the transducer) as a function of horizontal range. For a flat, horizontal seabed the depth can be taken as the range of the first (vertical) seabed echo, which is relatively easy to extract from the echo amplitude. Clearly this last expression is not defined for $r < d(x = 0)$.

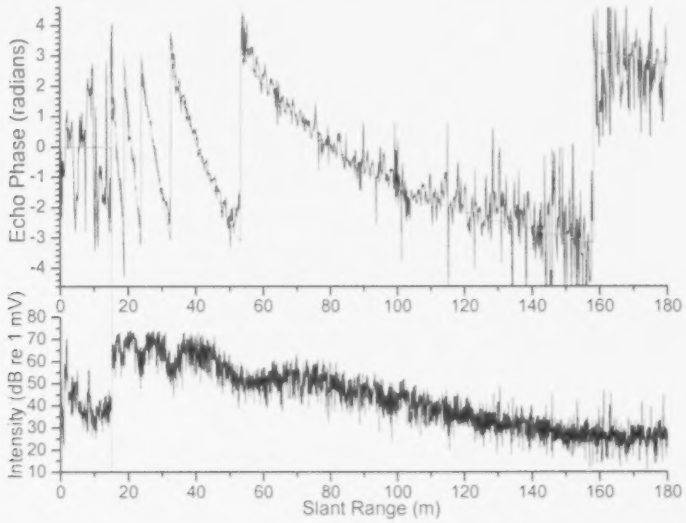


Figure 17 Single-ping phase and intensity vs. slant range for the 100-kHz port-side interferometric dipole, taken at 1401h, April 16th, 2002 near the entrance to Esquimalt harbour. Red line is range to seabed. Green line is reference phase computed assuming flat seabed at 15 m depth.

Figure 17 shows the result of this phase calculation for a single ping taken over a relatively flat seabed near the entrance to Esquimalt harbour. The water depth below the transducers, extracted from the Intensity vs. range curve, was 15.0 m. The figure shows excellent overall agreement between the measured and reference phase curves, particularly between the first seabed return at 15 m and approximately 150 m range. In particular, the measured phase at the point of the first seabed return is very close to $k*d*\sin(90°) - 10*\pi = 1.68$ radians. This lends confidence in the accuracy of the coherent demodulation scheme used in the receiver. Note that both phase curves wrap-around five times from 15 to 180 m range, with the phase multiple of 2π decreasing from 5 to 0 at each transition. Also, the $-\pi$ to $+\pi$ phase transitions occur at the same range as the interferometric nulls in the transmit beam pattern. At slant ranges beyond roughly 100 m the measured phase curve becomes increasingly noisy, implying decreasing signal-to-noise performance. Clearly, working in a shallow environment at ranges greater than roughly 10 times the water depth opens the possibility for multiple

surface- and seabed-reflected paths and surface scatter contamination. Reduction of this phase variance at longer range could be achieved through use of a longer pulse length.

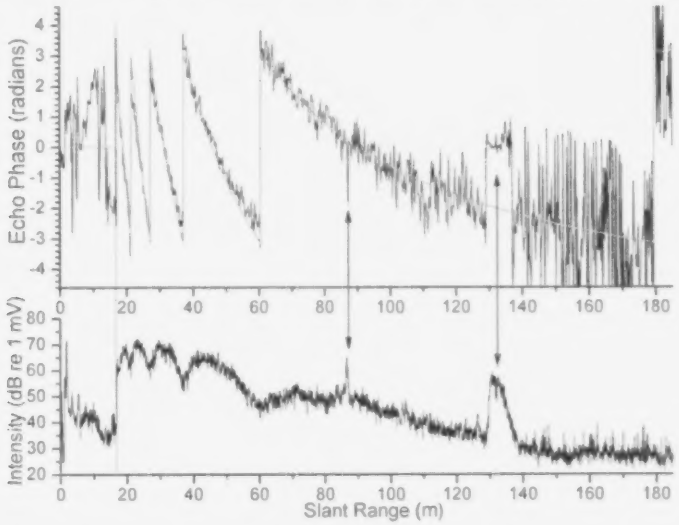


Figure 18 Single-ping phase and intensity vs. slant range for the 100-kHz port-side interferometric dipole, taken at 1350h, April 16th, 2002 near the entrance to Esquimalt harbour. Red line is range to seabed. Green line is flat seabed reference phase. Blue arrows denote intensity-phase anomalies.

Overall, deviations of the measured phase away from the seabed reference could be used to extract the angle to objects above bottom, as shown with an example in Figure 18. The measured phase is in close agreement with the flat seabed reference curve, except for two anomalous targets. Both of these phase anomalies have corresponding intensity anomalies. The largest target, spanning slant ranges from 129 to 137 m and having a roughly 20 dB intensity excess over the background, is likely a school of herring-like fish. At 130 m range (and assuming an 18 m seabed depth below the transducer), the seabed echo has a grazing angle of 7.9° (downwards). The measured phase angle within this target is approximately +0.1 radians, roughly 1.9 radians different from the seabed reference. If this phase angle is assumed to belong to the $n = 0$ phase wrap (as for the seabed at slant range > 180 m), then it corresponds to a target angle of 0.17°, placing the acoustic center of the fish school 17.6 m above the seabed (i.e. near the surface). If the $n = 1$ phase wrap is assumed, then the target angle would be 11°, placing the target below the seabed (which is impossible). The second, smaller target at 87 m slant range and roughly 0.5 m across has a phase angle of -1.8 radians. This is approximately 2.0 radians different from the seabed reference curve, and assuming the $n = 1$ phase wrap corresponds to an arrival angle of 7.7°. Since the seabed grazing angle at this range is 11.9°, this target could be located 6.5 m above the seabed. If the $n = 0$ phase wrap is assumed, then the target angle would be –3.1°, which would place the target above the water surface (which again is impossible). Thus, in both cases the phase-wrapping creates no ambiguity in target location. However, at closer range (i.e. for phase-wrap $n \geq 2$) there is the potential for several valid target locations in the water column. This problem could be partially alleviated by placing the transducers closer together.

6. Chirp Pulse Analysis

The use of linear swept-FM (*chirp*) pulses is a well-known technique for improving signal-to-noise and spatial resolution in backscatter sonars. This 4-channel, 100-kHz sonar system has a modest bandwidth of 10-kHz centred around 100-kHz. This system has the capability to transmit chirp pulses of variable length (up to 10 ms), which increase linearly in frequency from 95 to 105 kHz in 50 μs steps. The goal of using this pulse type and subsequent processing is to increase the time-bandwidth product, i.e. pulse-length τ x bandwidth Δf. This decorrelation process is usually accomplished in the frequency domain by multiplying the Fourier Transform (FT) of the pulse echo by the conjugate-FT of the transmit pulse replica, then computing the inverse-FT. This has the effect of applying a *matched filter* to the pulse echo, essentially time-compressing the chirp into a pulse of width equal to the inverse bandwidth. After decorrelation processing there should be a signal-processing gain (in dB) given by $10\log_{10}[\tau \cdot \Delta f]$, with a range resolution of $c / \Delta f$ (where c is the sound speed). For example, with a 10-kHz bandwidth and a 5-ms transmit pulse, the processing gain should be 17 dB with an effective pulse width of 0.1 ms.

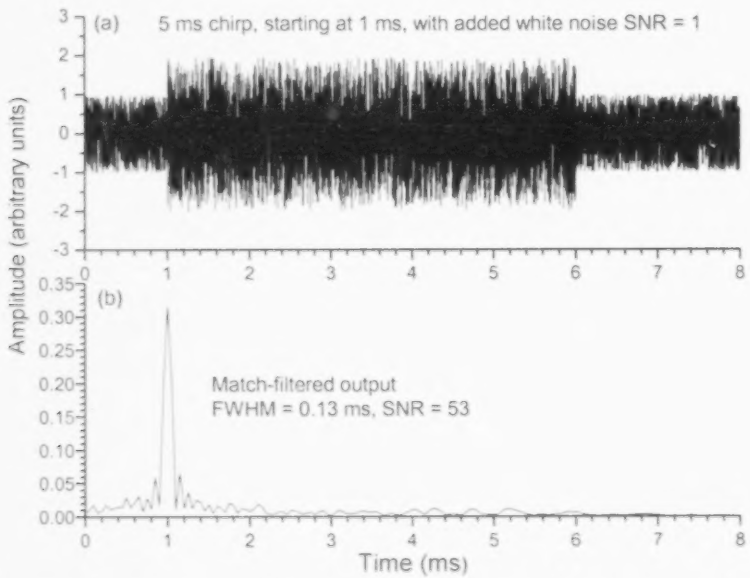

(a) 5 ms chirp, starting at 1 ms, with added white noise SNR = 1
Amplitude (arbitrary units)
(b)
Match-filtered output
FWHM = 0.13 ms, SNR = 53
Time (ms)

Figure 19 Results of synthetic chirp pulse analysis: (a) simulating a 5-ms x 10-kHz chirp pulse with 1-ms delay and added white noise of equal amplitude, (b) match-filtered output showing time compression to 0.13 ms pulse with processing gain of 53 (17.2 dB).

A numerical test was conducted to assess the effects of using the frequency-stepped chirp generation scheme utilized by this system. Synthetic pulses were generated using the same frequency-stepped scheme as utilized by the sonar system, i.e. dividing the 10-kHz bandwidth into 50-μs duration steps. The base synthetic pulse was calculated using a 1 μs sampling

interval, then mixed with sine and cosine versions of the 100-kHz carrier, low-pass filtered, and sub-sampled to a 20-kHz sample-rate. In the time-domain, the primary 95 to 105 kHz chirp waveform was essentially identical to the analytic waveform (calculated using $x(t) = \sin\left[2 \cdot \pi \cdot f_0 \cdot t + \pi \cdot \Delta f / \tau \cdot t^2\right]$, where t is time and f_0 is the 100-kHz center-frequency) for pulses longer than roughly 1 ms. Figure 19 shows an example of this synthetic pulse and the pulse compression. For a 5 ms pulse length, the 10 kHz bandwidth was divided into 100 steps of 100 Hz each. After match-filtering, the pulse now has resolution equivalent to a 0.13 ms pulse (9.7 cm), with a signal to noise increase by a factor of 50.

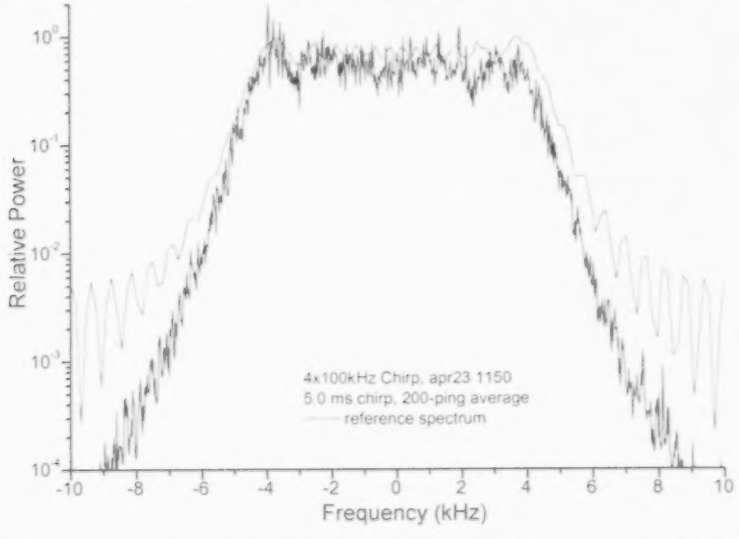


Figure 20 Comparison of measured and reference frequency spectra for 5.0 ms chirp pulse. Data averaged over 200 pings taken at IOS pier at 1150h April 23rd, 2002. Reference pulse replica was synthesized using 100 frequency steps of 100 Hz from 95 to 105 kHz, coherently homodyned.

An obvious test of the chirp sonar capability is whether the measured pulse echoes have the correct frequency content. Evaluation data using 1.0 and 5.0 ms pulse lengths was collected during acceptance tests at IOS on April 23rd, 2003. In these tests, the complex pulse echoes contained 6000 samples at 20 kHz rate, so a zero-padded 8192-pt FFT was used to compute the power-spectrum at each ping. This was then averaged over 200 pings and frequency-averaged by 8 to reduce variability. Example spectra using the 5.0 and 1.0 ms pulse lengths are shown in Figures 20 and 21. For comparison, spectra computed from the synthetic pulse replicas are shown. The two examples show excellent agreement between the measured and reference power-spectra in terms of spectral shape. In particular, note the difference in spectral shape between the two pulse lengths, i.e. the 1.0 ms pulse has a central peak with symmetric valleys in the pass-band and more pronounced roll-off outside of ±3 kHz, whereas the 5.0 ms pulse has a relatively flat pass-band with roll-off outside of ±4 kHz. Note that because of the receiver low-pass filters at ±5 kHz, the measured spectra fall-off faster than the reference outside the ±5 kHz pass-band. Also, the reference pulse spectra exhibit processing

side-lobes (obvious outside of ±6 kHz) due to the use of a rectangular window in the FFT calculation.

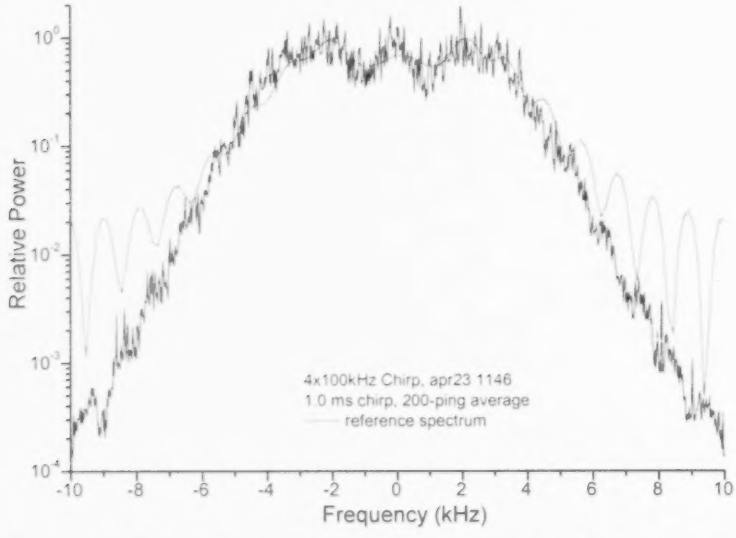


Figure 21 Comparison of measured and reference frequency spectra for 1.0 ms chirp pulse. Data averaged over 200 x 8192-pt FFT taken at IOS pier at 1146h April 23rd, 2002. Reference pulse replica was synthesized using 20 frequency steps of 500 Hz from 95 to 105 kHz, coherently homodyned.

7. Discussions and Recommendations

This report documents the delivery and some potential applications of a new, multi-purpose high-frequency sonar system, developed through a collaboration between Defence R&D Canada Atlantic and the Institute of Ocean Sciences (Fisheries & Oceans Canada). In addition to providing a conventional imaging sidescan capability, this sonar is phase-coherent, allowing such applications as Doppler velocity estimation and multi-element beam-forming. Furthermore, this sonar system has the capability for transmitting phase-encoded and swept-FM pulses. It's coherent data sampling, flexibility in deployment, and variable pulse types makes this system useful as a research tool for both seabed and ocean surface acoustic studies. In particular, the choice of 100-kHz acoustic frequency allows greater operating range (potentially in excess of 500 m) and a greater sensitivity to small bubbles near the ocean surface. This latter aspect makes the system extremely useful for studying ship wake and near-surface wave-breaking processes.

As an imaging sidescan, this 4 x 100-kHz system does not have the necessary along-track resolution, in essence beam-width, to reliably find seabed mines. The 3° transducer beam-width produced along-track resolution of order several meters, increasing with range, as opposed to the 10-cm resolution provided by the Klein 5500. Although capable of detecting the highlight and shadow of typical mines (as seen in Fig. 11), the low resolution does not allow discrimination of mines from background seabed clutter nor any ability to classify on the basis of shape. On the plus side, this 100-kHz system can see much farther (to at least 200 m range in the examples examined herein), and so would be useful for broad-area mapping of larger features such as rocky shoals. Moreover, through use of the interferometric capability, mapping of across-track seabed bathymetry profiles and the elevation angles to mid-water objects (such as fish schools) can be performed. Finally, with four separate channels the sonar has the capability for multi-aspect imaging, subject to the same resolution constraints as in the conventional sidescan mode.

The acceptance testing of this sonar system was purposely *quick and dirty*, producing less than ideal test data. For example the sidescan data collected in April 2002 were heavily contaminated with vessel roll and yaw artefacts, particularly accentuated by the multi-lobed interferometric footprint of the dipole geometry on April 16th. Clearly, a vessel-mounted configuration can only be used in situations with minimal sea state, and it is advisable to have ping-by-ping measurements of vessel pitch, roll, and heading. The latest version of the data acquisition software allows incorporation of GPS and gyrocompass data directly into the sonar data stream. Furthermore, in water depths greater than roughly 20 m, the sonar altitude above the seabed produced a grazing angle that was too large for detection of seabed objects via shadows, as is usually performed with sidescan sonars.

The newly implemented chirp-pulse feature appeared to function as expected. One question answered in this work was to feasibility of the *stepped-FM* technique (constructing the pulse from discrete 50 μs frequency steps) for generating the frequency sweep. Numerical synthesis of the stepped-FM pulse showed essentially identical decorrelation properties to ideal chirp pulses, and the measured backscatter spectra had very similar frequency content to reference spectra.

In addition to the above general comments, there are a number of specific recommendations for improvement and further testing of the system:

1. A post-processing software suite should be developed, with capabilities of data replay, chirp-pulse decorrelation, Doppler velocity calculation for simple and coded-pulses, and interferometric processing. This software should also allow output of sidescan image data in a standardized format.
2. Specific verification of the chirp-pulse resolution and SNR enhancement could be performed through controlled tank tests.
3. An acoustic backscatter calibration of the four channels could be performed through measurement of the echoes from specific calibration targets, either in a test tank or in the field.
4. In addition to the chirp and Barker coded pulse transmission capability, the ability to transmit long phase-encoded pseudo-random sequences should be implemented. This would allow precise travel-time estimates in one-way propagation experiments.

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Appendix 1: Sonar Binary File Formats

The four-channel data acquisition system stored raw data in a unique binary format. File naming convention was MMDDHHmm.dat, (month, day, hour, minutes), derived from the data acquisition PC clock. Specification below based on 'C' language commands. Values in brackets are typical values.

For data collected during April and November 2002 trials:

Leader: (once at beginning of file)

Carrierfrequency	float	4 bytes	(100000 Hz)
SampleRate	float	4 bytes	(20000 Hz)
MaxTime	float	4 bytes	(300 ms)
DataLengthPerChan	long int	4 bytes	(6000 samples)

```
struct PIC_DATA{
        int CodeLength, CyclesPerBit, TvgX, TvgY1, TvgZ1;
        int TvgY2, TvgZ2, TvgY3, TvgZ3;
        int BarkCode, RxTx;                    //code type, status flag
        float PingRate, PingRateA;             //disregard A value
        }
```

note: Tvg = time varying gain, param 1 is delay time (ms), param 2 is rise time (ms), param 3 is fixed gain offset (dB). Disregard Y2, Z2, Y3, Z3 values.

Data: (one group for each ping)

DayTime[12]	char	12 bytes (e.g. 12:04:14.12)
Info[7]*	long int	7 * 4 bytes
(note: Info[0]= TvgX;	Info[1]= TvgY1;	Info[2]= TvgZ1;
Info[3]= TvgY2;	Info[4]= TvgZ2;	Info[5]= TvgY3;
Info[6]= TvgZ3;)		
DataI[channel 1]	unsigned short	DataLengthPerChan*2bytes
DataQ[channel 1]	unsigned short	DataLengthPerChan*2bytes
DataI[channel 2]	unsigned short	DataLengthPerChan*2bytes
DataQ[channel 2]	unsigned short	DataLengthPerChan*2bytes
DataI[channel 3]	unsigned short	DataLengthPerChan*2bytes
DataQ[channel 3]	unsigned short	DataLengthPerChan*2bytes
DataI[channel 4]	unsigned short	DataLengthPerChan*2bytes
DataQ[channel 4]	unsigned short	DataLengthPerChan*2bytes

* during Nov. 2002 data this vector reduced to 6 values.

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(U) This report documents the design and features of a new, four-channel, coherent 100-kHz sidescan sonar system developed in a collaboration between Defence R&D Canada – Atlantic the Institute of Ocean Sciences (Fisheries & Ocean Canada). This system supports four separate 100-kHz sidescan transducers, with coherent in-phase and quadrature sampling of each channel at 20,000 samples per second. The system has the capability to transmit uncoded, phase-modulated Barker-coded, and swept-FM (chirp) pulse types, with user selectable pulse-lengths up to 10 ms. As part of the acceptance tests, several sidescan sonar applications were demonstrated, including conventional and multi-aspect-angle sidescan, seabed bathymetry through interometric processing, and the use of chirp pulses. The primary tests were conducted from a small boat in the vicinity of Esquimalt, B.C. in April, 2002. The relatively large horizontal beam-width (3) of the transducers was found to provide insufficient along-track resolution for reliable seabed mine detection, particularly when compared to very-high-frequency imaging sonars such as the Klein 5500. However, the sonar demonstrated a much greater operational range, in excess of 200 m per side. The use of port and starboard interferometric dipoles was able to map the across-track seabed slope at ranges up to 200 m in roughly 20 m water depth. Measured backscatter frequency spectra were found to have nearly identical frequency content to reference chirp-pulse spectra.

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